Radiation Physics Note 46

A Study of the Accumulation and Reduction of Radon and Its Daughter Products in an Underground Tunnel

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Introduction

This study will show how ventilation affects radon and its daughter product concentrations in a model underground tunnel having a circular cross sectional area and a radius, r, of 150 cm. The presentation will be divided into three parts.

I. Determination of the daughter product buildup in a constant source of radon.

II. Determination of the daughter product buildup in a volume of fresh air into which radon is being introduced.

III. Determination of ventilation times and rates necessary to reduce maximum equilibrium radon and daughter product concentrations to levels which correspond with accepted standards.

In part II a simple theoretical model of ventilation will be applied to radon and daughter product concentration levels in the tunnel. This model will assume fresh air is forced into the tunnel so that radon laden air is linearly displaced (no mixing) in order to provide an upper limit for the effects of ventilation. The accumulation of daughter products in the fresh air will depend on the concentration level that the radon gas rises to. It will be valuable to understand how the daughter products accumulate for a given concentration of radon. Part I determines this information.

I. Determination of the Daughter Product Buildup in a Constant Source of Radon

The equation which relates the time rate of change of radon atoms in the unventilated tunnel to the rate of change of atoms diffusing through the wall and the rate of decay of the radon atoms is:

$$\frac{dN_{Rn}}{dt} = S - N_{Rn}\,\lambda_{Rn}$$

where

$$R = \frac{FA}{\lambda_{Rn}}$$

N_{Rn} = Number of radon atoms present.

S = Rate of change of atoms diffusing through the wall per unit time.

λ_{Rn} = Decay constant for radon.

F = Radon activity diffusing through the tunnel walls per unit area per unit time.

A = Area of tunnel walls

The solution for the initial conditions which state that t=0, N_{max}=0 is:

$$N_{Rn} = N_{max}\,(1 - 1^{-\lambda_{Rn} t}).$$

At equilibrium: $\frac{dN_{Rn}}{dt} = 0 = N_{Rn}\,\lambda_{Rn} = S.$

The concentration of radon in the tunnel at equilibrium will be:

$$C_{Rn} = \frac{N_{Rn}\,\lambda_{Rn}}{V} = \frac{S}{V} = \frac{FA}{V\lambda_{Rn}}$$

where

C_{Rn} = Concentration of radon in tunnel

V = Volume of the tunnel.

For the model tunnel: $A = 2\Pi\ rl$

$V = \Pi r^2 l$

where l = length of the tunnel.

Typical values for F are on the order of 10^{-16} Ci/sec·cm^2.[1] Using values of r = 150 cm and $\lambda_{Rn} = 2.1 \times 10^{-6}$/sec gives an equilibrium radon concentration of:

$$C_{Rn} = 635\ ^{pCi}/_{l}.$$

The equations for the accumulation of daughter products in a constant source of radon are according to Evans.[2]

$$C_A = \frac{I}{V}A = C_{Rn}(1-1^{-t/4.39\ min})$$

$$C_B = \frac{I}{V}B = C_{Rn}(1+0.1281^{-t/4.39\ min}-1.1281^{-t/38.6\ min}).$$

$$C_C = \frac{I}{V}C = C_{Rn}(1-0.02351^{-t/4.39\ min}-4.25941^{-t/38.6\ min}+3.28291^{-t/28.4\ min}).$$

where C_A, C_B, and C_C are the concentrations of RaA, RaB, and RaC respectively and I_A, I_B and I_C are the activities of the daughter products.

Since the deposition of energy by alpha particles from the decay of the daughter products is potentially dangerous to humans, it is advantageous to use a unit which is defined in terms of this energy. One working level (WL) is any combination of the short-lived decay products of radon (RaA, RaB, RaC, and RaC′) in one liter of air that will result in the ultimate emission by them of 1.3×10^5 MeV of alpha particle energy. The alpha emitter RaC′ makes a neglible contribution to this energy total because of its very short half-life and the relatively small number of RaC′ atoms present at equilibrium. The amount of energy 1.3×10^5 MeV can ultimately be delivered by the short-lived decay products of radon that are in radioactive equilibrium with 100 pCi of radon.

According to Evans,[3] "although the WL unit is derived by using an hypothetical equilibrium atmosphere, the unit is to be used for any mixture of the short-lived decay products of radon." The working levels of daughter products as a function of concentration are:

$$WL_A = 0.00103\ {}^{I_A}/V = 0.00103\ C_A$$
$$WL_B = 0.00507\ {}^{I_B}/V = 0.00507\ C_B$$
$$WL_C = 0.00373\ {}^{I_C}/V = 0.00373\ C_C$$

The total working level accumulated, WL_T, is the sum of the working levels of the daughter products WL_A, WL_B and WL_C.

For a constant source of radon on the order of 10^{-16} $^{Ci}/sec{\cdot}cm^2$ in the unventilated model tunnel, assuming the equilibrium concentration of radon is present with no accumulated daughter products at t=0, 1/3 WL_T will be reached in about 3 minutes, 1 WL_T in about 10 minutes and 98% of the equilibrium value of 6.35 WL in about 7 hours. See Figure 1 and Graph I. In the absence of ventilation the maximum equilibrium working level total can be expected to reach 6.35 WL, or 635 $^{pCi}/1$ of radon for a deep underground tunnel of 150 cm radium and a typical radon flux of 10^{-16} $^{Ci}/sec{\cdot}cm^2$.

II. Determination of the Daughter Product Buildup in a Volume of Fresh Air into which Radon is being Introduced

In order to determine the maximum effect that ventilation can have on the activity concentrations, a simple theoretical model for ventilation of the model tunnel will be employed. If the outside fresh air is forced into the tunnel so that it linearly displaces the radon laden air (no mixing), the accumulation of the daughter products will depend on the amount of radon that the fresh air will pick up for the time it moves through the tunnel. Refer to Figure 2.

For a typical flux of 10^{-16} $^{Ci}/_{sec\cdot cm^2}$ and initial conditions stating that at t=0, C_{max}=0, the equation for the buildup of radon activity concentration is:

$$C_{Rn} = 635\ ^{pCi}/_{l}\ (1-1^{-\lambda_{Rn}t}).$$

The accumulation of daughter products in the volume of fresh air will be the product of the radon activity concentration with respect to the residence time of the fresh air in the tunnel and the relative working level factor for this concentration determined from Graph I.

For example:

A residence time t=4.39 minutes for the fresh air will produce an accumulation of daughter product working levels of:

$$WL_T = C_{Rn}(4.39 \text{ min}) \times \frac{WL_T(4.39 \text{ min})}{6.35 \text{ WL}}$$

$$WL_T = 0.349 \frac{pCi}{l} (0.086) = 0.03 \frac{pCi}{l} = 0.0003 \text{ WL}$$

instead of the 0.55 WL that would accumulate in a constant source of radon at equilibrium with no ventilation. Graph II shows that under the conditions of ventilation with no mixing 1/3 WL would be obtained in 7 hours and 19 minutes, 1 WL in 23 hours and 10 minutes and 98% of the equilibrium value of 6.35 WL in about 22 days.

The role that ventilation plays in reducing the concentration levels of radon and its daughter products can be seen when the extreme cases for ventilation for this radon flux are compared. Under the conditions of a constant source of radon in an unventilated tunnel 1/3 WL of daughter products will accumulate in about 3 minutes while in the case of ventilation with no mixing it will take 7 hours and 19 minutes to reach 1/3 WL.

This analysis can be applied to actual rock samples taken from the area just west of the Fox River near Aurora, Illinois. The nuclear counting laboratory reports located in the appendix under Work Req #840622-55 for sample 1, Work Req #840625-56 for sample 2 and Work Req #840717-63 for sample 3 provide information from which the radon flux into the tunnel, F, can be estimated. The reports provide the value of radium activity per unit mass, I_{Ra}/m, for each sample. Since the rate of decay of ^{226}Ra equals the rate of production P_{Rn} of ^{222}Rn (radon).

$$\frac{P}{m}_{Rn} = \frac{I}{m}_{Ra} \lambda_{Ra}$$

To find the rate of production of ^{222}Rn per unit volume:

$$\frac{P}{m}_{Rn} D = \frac{I}{m}_{Ra} \lambda_{Ra} D$$

where D is the density of rock.

According to Fry,[4] "approximately 25% of the radon produced is released from tailings and effectively only the radon produced in the first meter depth will find its way into the atmosphere."

The radon flux from rock should be less than that from tailings or less than:

$$F = (.25)\ (10^2 cm)\ \frac{P_{Rn}}{m}\ D$$

or

$$F = 25\ \frac{I_{Ra}}{m}\ \lambda_{Ra}\ D\ \frac{pCi}{sec \cdot cm^2}$$

Values of radon flux from these samples using this equation are:

Maquoketa: $F = 0.84 \times 10^{-16}\ Ci/sec \cdot cm^2$

Silurian: $F = 0.21 \times 10^{-16}\ Ci/sec \cdot cm^2$

Galena-Plattville: $F = 0.43 \times 10^{-16}\ Ci/sec \cdot cm^2$

<u>Time to Reach 1/3 Working Level for Different Wall Materials in an Underground Tunnel</u>

Wall Material For Tunnel Rock Formation	Radon Flux ($\times 10^{-16}\ Ci/sec \cdot cm^2$)	Equil. Radon Conc. (pCi/l)	Time to Reach 1/3 Working Level in an Unventilated Tunnel For an Equal. Conc. of R_m with Daughter Products Removed (Fm. Graph I.)	Time to Reach 1/3 Working Level for Ventilation with No Mixing (Fm. Graph II.)
Maquoketa	0.84	530	3 minutes	8 hours
Silurian	0.21	136	16 minutes	39 hours
Galena-Plattville	0.43	271	7 minutes	18 hours

These comparisons indicate the effect that ventilation has on the accumulation of radon and daughter products. A more realistic model for ventilation effects in the tunnel would incorporate mixing and produce accumulation times for a given concentration somewhere between the extremes.

III. Determination of Ventilation Times and Rates Necessary to Reduce Maximum Equilibrium Radon and Daughter Product Concentration of Levels which Correspond with Accepted Standards

A model (see Fig. 3) closer to what actually happens in a ventilated tunnel would relate the rate of change of radon activity concentration, dC_{Rn}/dt, to the rate of flow of radon activity into a unit volume of tunnel air K, the rate of decay of radon activity concentration due to ventilation, $\lambda_v C_{Rn}$, where λ_v is the elimination constant due to ventilation. This relation can be expressed as:

$$\frac{dC_{Rn}}{dt} = K - \lambda_{Rn} C_{Rn} - \lambda_v C_{Rn} \qquad \text{where } K = \frac{FA}{V}.$$

The solution for initial conditions which state that at t=0, C_{max} = equilibrium concentration with no ventilation is:

$$C_{Rn}(t) = \frac{K}{(\lambda_{Rn}+\lambda_v)} \quad 1 + \left[\frac{C_{max}(\lambda_{Rn}+\lambda_v)-K}{K}\right] e^{-(\lambda_R+\lambda_v)t}$$

For equilibrium: $\frac{dC_{Rn}}{dt} = 0 \Rightarrow C_{Rn} = \frac{K}{(\lambda_{Rn}+\lambda_v)}$.

Similar equations can be written for concentration levels of daughter products:

$$C_A = K/(\lambda_A+\lambda_v).$$

$$C_B = K/(\lambda_B+\lambda_v).$$

$$C_C = K/(\lambda_C+\lambda_v).$$

The working levels associated with these concenrations can be completed as before on page 4.

If the ventilation system can be designed to provide an elimination constant λ_v = 1 room change/hour, the equilibrium radon activity concentrations and the equilibrium working level totals computed for each of the three rock samples studied will be as follows:

Radon and Daughter Product Concentrations for Different Wall Materials at a Ventilation Rate of 1 Room Change/hour.

	Radon Flux F ($\times 10^{-16}$ Ci/sec·cm^2)	Equil. Radon Conc. C_{Rn} (pCi/l)	Equil. Working Level Total WL_T
Maquoketa	0.84	3.99	0.013
Silurian	0.21	1.02	0.0013
Galena-Plattville	0.43	2.03	0.007

The equilibrium working level totals are very low at the given ventilation rate. The time dependent factor for the daughter product activity concentration buildup can be neglected when ventilation on this order is provided. Ventilation affects concentration levels in two ways. It causes the buildup to equilibrium to occur more slowly and it lowers the value that these concentrations can ultimately rise to. It is the equilibrium value which now becomes important.

Department of Energy Order 5480.1A, Chapter 11, pg. 3 lists a standard of 5 rem/yr, 3 rem/calendar quarter, whole body exposure for occupationally related exposures. It also lists a concentration guide for radon gas in air under controlled conditions of 100 pCi/l. This is the standard set for workers putting in 170 hours per month.

A worker putting in 170 hours per month at a concentration of one working level (1 WL) is said to have received an exposure of 1 working level month (1 WLM). A more conservative standard for exposure rates is listed as 4 WLM/yr.[5] This exposure rate implies a concentration standard of 1/3 WL for workers putting in 170 hours per month for 12 months.

These values can be summarized:

$$1 \text{ WLM} = \frac{(170 \text{ hours work})}{\text{month}} \times 1 \text{ WL}$$

$$\frac{4 \text{ WLM}}{\text{yr}} \times \frac{1 \text{ yr}}{12 \text{ mo}} = 1/3 \text{ WL}$$

For radiation protection purposes, an occupational exposure of 1 WLM can be considered to be the equivalent of 1.25 rem of whole body dose. For actual organ dose assessment, an exposure of 1 WLM delivers about 4 rem to the lungs.[6]

These standards and conversion factors can be applied to various cases of ventilation for each of the rock samples. Table I shows the relationship between residence time for a volume of fresh air in the tunnel and the working level totals with their associated exposure conversions for each sample of rock. Table II relates various ventilation constants to the working level totals and their associated exposure conversions for each sample of rock. The tables show how relatively low ventilation rates affect working level buildups for samples of rock taken from the area.

Understanding how ventilation rates can affect equilibrium concentration levels, it may be interesting to look at the relation for radon activity concentration at a given time, $C_{Rn}(t)$, in terms of initial conditions which specify that at t=0, C_{max} = equilibrium concentration with no ventilation for a given sample of rock. These conditions approximate the case where the tunnel may be closed for an extended period of time during which the radon activity concentrations and daughter product working levels would reach their unventilated equilibrium levels.

Writing $C_{Rn}(t)$ in terms of these initial conditions and solving for the time, t, provides a method for determining the time required to reach a certain concentration at a given ventilation rate for each rock sample. The expression for the time is:

$$t = \frac{\ln\left[\dfrac{\dfrac{K}{(\lambda_{Rn}+\lambda_v)} - C_{Rn}(t)}{\dfrac{K}{(\lambda_{Rn}+\lambda_v)} - C_{max}}\right]}{-(\lambda_{Rn}+\lambda_v)}$$

Graphs III, IV and V allow an estimation of the time that must be provided to reduce the radon level concentrations from a maximum equilibrium value associated with each type of rock to one of the four selected concentrations for a given ventilation rate. It can be seen in Graph III that ventilation constants ranging from 5.56×10^{-3}/min (1/3 room change/hr) to 100×10^{-3}/min (6 room change/hr) will reduce a concentration of 531.7 pCi/l, the largest equilibrium concentration for the rock samples studied, to 33 pCi/l in times ranging from 563 minutes to 28 minutes.

Summary

Radon concentrations are dramatically affected by ventilation. Under equilibrium conditions an activity of 100 pCi/l of radon is equivalent to 1 WL. Exposure standards of 4 WLM per year imply working for 170 hours per month, 12 months per year at a concentration of 1/3 WL or 33 pCi/l of radon activity.

For the cases of no ventilation and ventilation with no mixing the time required to reach 1/3 WL is important. Using the Maquoketa bedrock as an example, it would take only 3 minutes to reach 1/3 WL for the conditions of a constant source of radon in an unventilated tunnel with no daughter products present initially. The time required to reach 1/3 WL for the case of ventilation with no mixing would be about 8 hours. The model for ventilation with mixing would produce accumulation times between these extremes. However, once continuous ventilation on the order of 1 room change/hr is provided, the time required to buildup to 1/3 WL is irrelevant since the equilibrium working level total will only reach 0.013 WL.

It then becomes a question of how long it would take to reduce an equilibrium concentration to the accepted standard after ventilation has commenced. For the Maquoketa bedrock, the unventilated equilibrium conentration can be reduced to 1/3 WL in about 3 hours if ventilation on the order of 1 room change/hr is provided. Other radon flux values, accumulation times, reduction times and ventilation rates can be determined by the same methods.

References:

1. Evans, R. D., "Engineers Guide to the Elementary Behavior of Radon Daughters," Health Physics 38 (June), p. 1176 (1980).

2. Evans, Ibid, p. 1179.

3. Evans, Ibid, P. 1184.

4. Fry, R. M., "Radiation Hazards in Uranium Mining and Milling," Atomic Energy (Oct.), p. 29 (1975).

5. Fry, Ibid, p. 26.

6. Walsh, P. J. "Dose Conversion Factors for Radon Daughters," Health Physics 36 p. 601 (1979).

Appendix

1. Table I. - Working Levels for Different Residence Times of Fresh Air for Rock Samples from the Auroraland Area.

2. Table II. - Working Levels for Selected Ventilation Rates of Rock Samples from the Auroraland Area.

3. Graph I. - Buildup of Working Levels vs. Time; Based on a Constant Concentration of Radon. At t=0, C_{Rn} = 635 pCi/l.

4. Graph II. -Buildup of Working Levels vs. Time; Based on a Time Dependent Concentration of Radon. At t=0, C_{Rn}=0; C_{max} = 635 pCi/l.

5. Graph III. - Time Required to Reach a Given Radon Conentration vs. Ventilation Rate Based on an Equilibrium Concentration of 531.7 pCi/l.

6. Graph IV. - Time Required to Reach a Given Radon Concentration vs. Ventilation Rate Based on an Equilibrium Concentration of 136.1 pCi/l.

7. Graph V. - Time Required to Reach a Given Radon Concentration vs. Ventilation Rate Based on an Equilibrium Concentration of 271.0 pCi/l.

8. Work Req #840622-55.

9. Work Req #840625-56.

10. Work Req #840717-63.

11. Figure 1. - Model for a Closed Tunnel with an Equilibrium Concentration of Radon and No Accumulated Daughter Products Initially.

12. Figure 2. - Model for Ventilation with No Mixing.

12. Figure 3. - Model for Ventilation with Mixing.

Table I. Working Levels for Different Residence Times of Fresh Air for Rock Samples from the Auroraland Area.

t Residence time for air in tunnel		Maquoketa bedrock non-ventilated equil. level = 531.7 $\frac{pCi}{l}$				Silurian Dolemite bedrock non-ventilated equil. level = 136.1 $\frac{pCi}{l}$				Galena-Plattville bedrock non-ventilated equil. level = 271.0 $\frac{pCi}{l}$			
hrs.	(min.)	WL_T	$\frac{WLM}{yr.}$	$\frac{rem*}{yr.}$	$\frac{mrem}{hr.**}$	WL_T	$\frac{WLM}{yr.}$	$\frac{rem*}{yr.}$	$\frac{mrem}{hr.}$	WL_T	$\frac{WLM}{yr.}$	$\frac{rem}{yr.}$	$\frac{mrem}{hr.}$
0.5	30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.0	60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.0	120	0.08	0.96	1.20	0.60	0.02	0.24	0.30	0.15	0.04	0.48	0.60	0.30
4.0	240	0.16	1.92	2.40	1.20	0.04	0.48	0.60	0.30	0.08	0.96	1.20	0.60
8.0	480	0.32	3.84	4.80	2.40	0.08	0.96	1.20	0.60	0.16	1.92	2.40	1.20
16.0	960	0.58	6.96	8.70	4.35	0.15	1.80	2.25	1.13	0.30	3.60	4.50	2.25
32.0	1920	1.09	13.08	16.35	8.18	0.28	3.36	4.20	2.10	0.56	6.72	8.40	4.20
64.0	3840	2.02	24.24	30.30	15.15	0.52	6.24	7.80	3.90	1.03	12.36	15.45	7.73
128	7680	3.22	38.68	48.35	24.18	0.82	9.84	12.30	6.15	1.64	19.68	24.60	12.30
256	15360	4.47	53.64	67.05	33.53	1.14	13.68	17.10	8.55	2.28	27.36	34.20	17.10
512	30720	5.16	61.92	77.40	38.70	1.32	15.84	19.80	9.90	2.63	31.56	39.45	19.73

Example:

Residence time for air in tunnel t = 8.0 hrs (480 min.)
Maquoketa Bedrock (non-ventilated equilibrium level = 531.7 $\frac{pCi}{l}$)

1. Read the value of WLT/5.317 WL from Graph II which is 0.06.
2. Multiply this value by 5.317 WL.

(.06) (5.317 WL) = 0.32 WL

*Based on 4 WLM equivalent to 5 rem whole body exposure.
**Equivalent dose rate based on 2000 hour/year exposure.

Table II. Working Levels for Selected Ventilation Rates of Rock Samples from the Auroraland Area.

λ_v		Maquoketa bedrock non-ventilated equil. level = 531.7 $\frac{pCi}{1}$				Silurian Dolemite bedrock non-ventilated equil. level = 136.1 $\frac{pCi}{1}$				Galena-Plattville bedrock non-ventilated equil. level = 271.0 $\frac{pCi}{1}$			
1/min ($\times 10^{-3}$)	1/hr	WL_{Teq}	WLM/yr.	rem*/yr.	mrem/hr.**	WL_{Teq}	WLM/yr.	rem/yr.	mrem/hr.	WL_{Teq}	WLM/yr.	rem/yr.	mrem/hr.
5.56	1/3	.01722	.213	.266	.133	.00440	.053	.066	.033	.00877	.105	.131	.066
6.67	2/5	.01669	.200	.250	.125	.00426	.051	.064	.032	.00850	.102	.128	.064
8.33	1/2	.01596	.192	.240	.120	.00407	.049	.062	.031	.00812	.097	.121	.061
11.1	2/3	.01487	.178	.223	.112	.00379	.045	.056	.028	.00757	.091	.114	.057
16.7	1	.01308	.157	.196	.098	.00334	.040	.050	.025	.00666	.080	.100	.050
33.3	2	.00965	.116	.145	.073	.00246	.030	.038	.019	.00491	.059	.074	.037
100.0	6	.00476	.057	.071	.036	.00121	.015	.019	.010	.00242	.029	.036	.018

Example: For $\lambda_v = 16.7 \times 10^{-3}$/min., Equil. Level = 531.7 $\frac{pCi}{1}$

$WL_T = WL_A + WL_B + WL_C = 0.00103\ C_A + 0.00507\ C_B + 0.00373\ C_C$

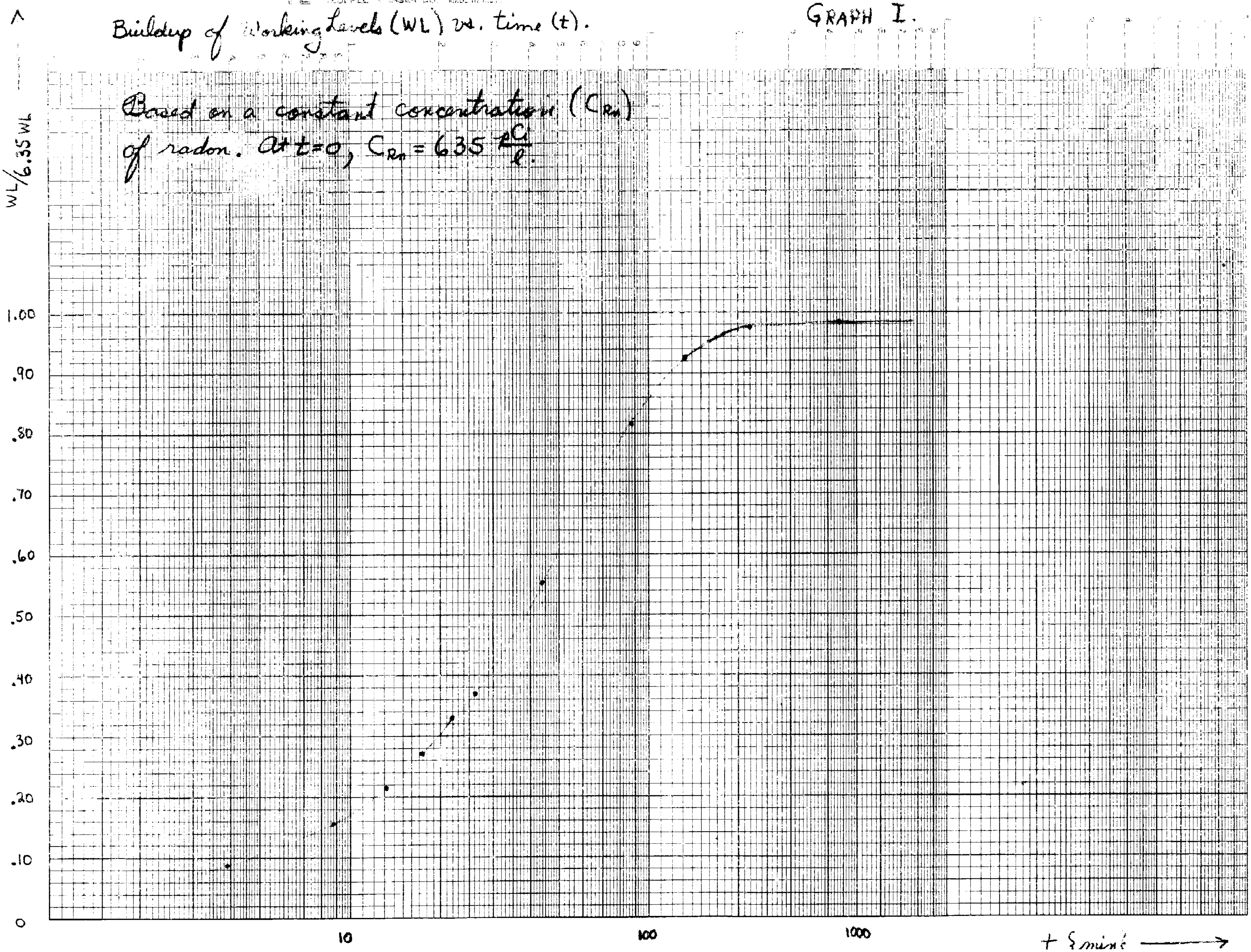
$C_A = K/(\lambda_A + \lambda_v)$ $C_B = K/(\lambda_B + \lambda_v)$ $C_C = K/(\lambda_C + \lambda_v)$

$C_A = 0.274$ pCi/1 $C_B = 1.573$ pCi/1 $C_C = 1.291$ pCi/1

$WL_T = 0.00028 + 0.00798 + 0.00482 = 0.01308$

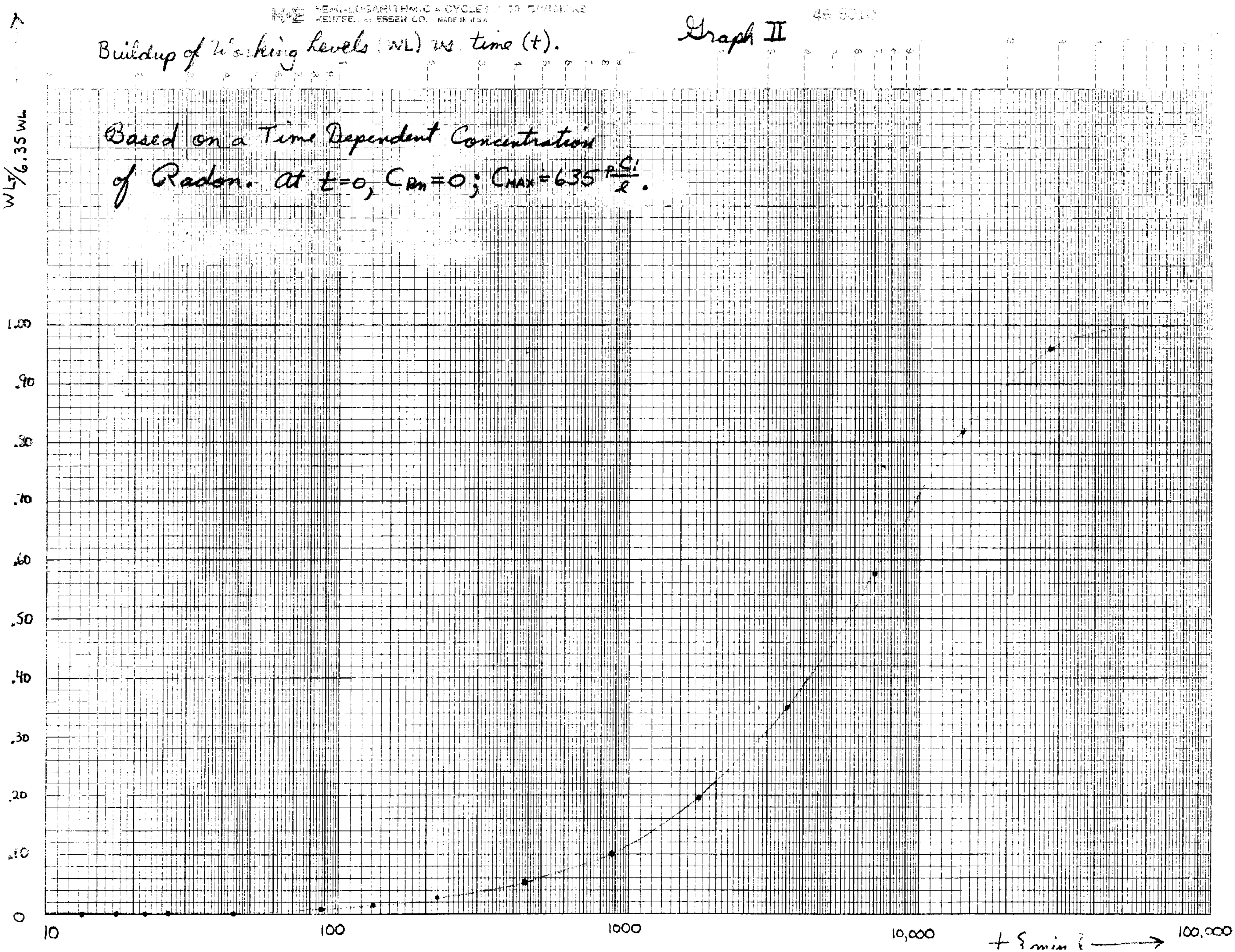
*Based on 4 WLM/yr equivalent to 5 rem whole body exposure.
**Equivalent dose rate based on 2000 hour/year exposure.

GRAPH I.



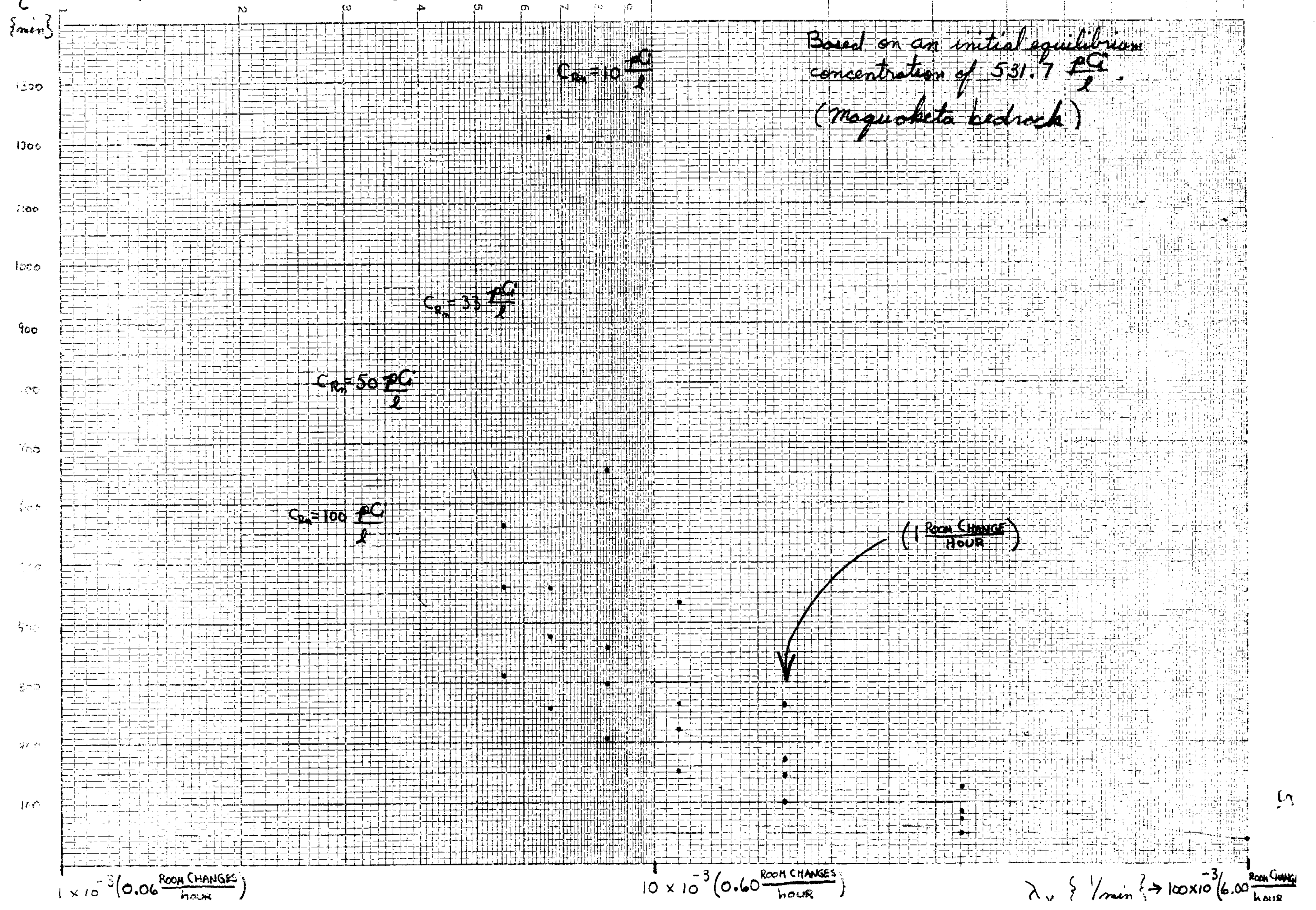
Buildup of Working Levels (WL) vs. time (t).
Based on a constant concentration (C_{Rn}) of radon. At $t=0$, $C_{Rn} = 635 \frac{pCi}{l}$.
WL/6.35 WL
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
10
100
1000
t (mins)

Graph II


K+E SEMI-LOGARITHMIC 4 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 6213
Buildup of Working Levels (WL) vs time (t).
Based on a Time Dependent Concentration
of Radon. At t=0, C_Rn=0; C_MAX = 635 pCi/l.
WL_T/6.35 WL
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
10
100
1000
10,000
100,000
t {min} →

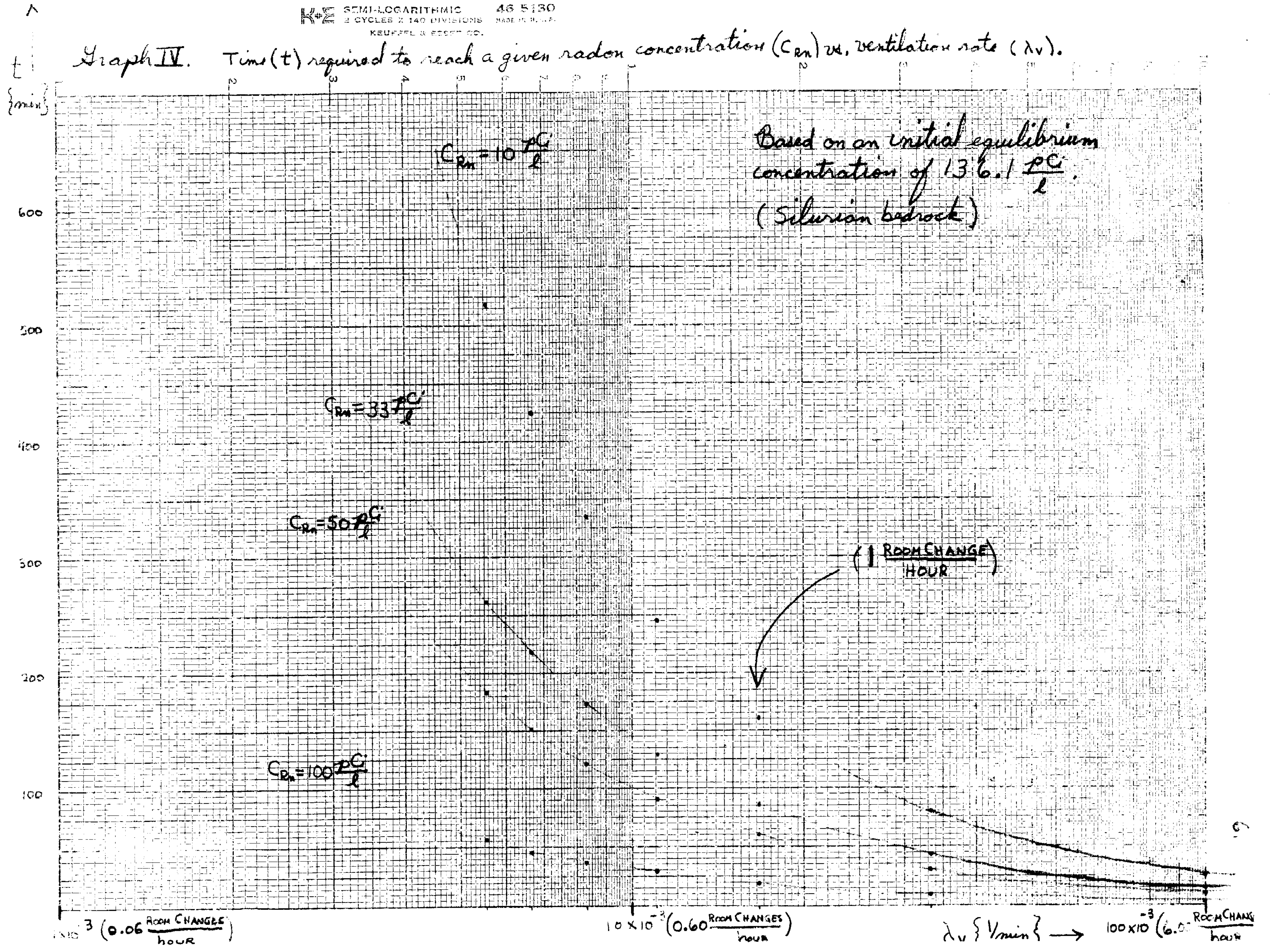
K+E SEMI-LOGARITHMIC 46 5130
2 CYCLES X 140 DIVISIONS MADE IN U.S.A.
KEUFFEL & ESSER CO.

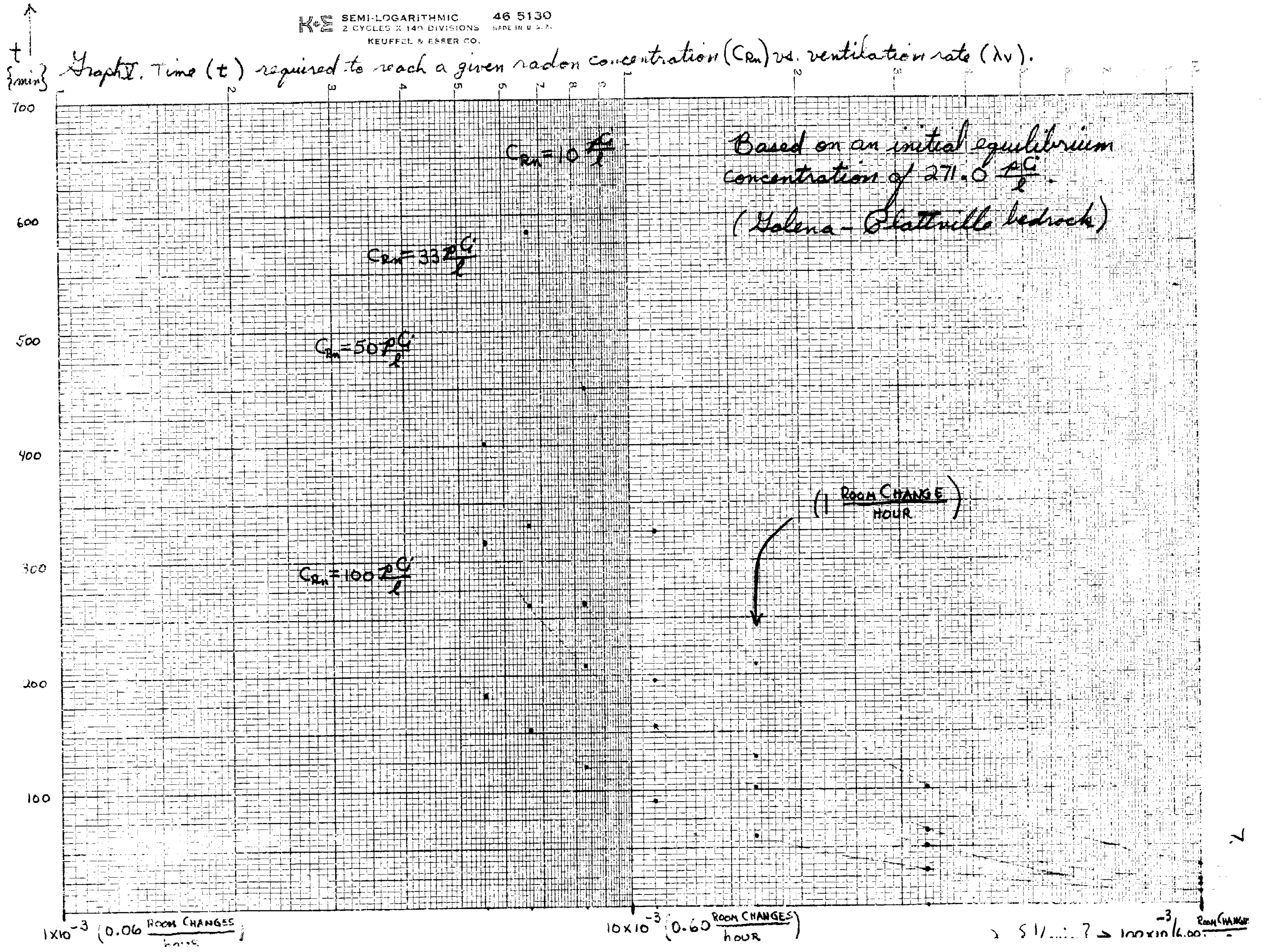
Graph III. Time (t) required to reach a given radon concentration (C_{Rn}) vs. ventilation rate (λ_v).



5.

Graph IV. Time (t) required to reach a given radon concentration (C_{Rn}) vs. ventilation rate (λ_v).




K+E SEMI-LOGARITHMIC 46 5130
2 CYCLES X 140 DIVISIONS MADE IN U.S.A.
KEUFFEL & ESSER CO.
Graph V. Time (t) required to reach a given radon concentration (C_{Rn}) vs. ventilation rate (λ_v).
t {min}
700
600
500
400
300
200
100
Based on an initial equilibrium concentration of 271.0 pCi/l.
(Galena - Platteville bedrock)
C_{Rn} = 10 pCi/l
C_{Rn} = 33 pCi/l
C_{Rn} = 50 pCi/l
C_{Rn} = 100 pCi/l
(1 ROOM CHANGE / HOUR)
1x10⁻³ (0.06 ROOM CHANGES / hour)
10x10⁻³ (0.60 ROOM CHANGES / hour)
100x10⁻³ (6.00 ROOM CHANGES / hour)

Fermilab

Nuclear Counting Laboratory
Analysis Report

Work Req# 840622-55	Job# 13	Date: 7/6/84
Submitted by: Sam Baker	Wkbk Location: #19 p 137	

Maquoketa bedrock from DeKalb County 6/22/84.
Elmer Larson's quarry.

Counted 61000 seconds at 1 cm from Ge(Li)#1.
256.94 g in 125 ml polyethylene bottle.
Calculated for 295, 352, and 609 keV.
Weighted average for Ra 226 = 0.57 ± .04 pCi/g.
Density = 2.8 g/cm^3 (5.3 x background) (6% system uncertainty included)

cc: R. Allen
S. Baker
J. Baldwin

Fermilab

Nuclear Counting Laboratory
Analysis Report

Work Req# 840625-56	Job# 13	Date: 7/6/84
Submitted by: Sam Baker	Wkbk Location: #19 p 136	

Silurian Dolemite Bedrock, obtained by L. Coulson on May trip. Counted in petri dish geometry for 159270 seconds (3 runs) at 1 cm from Ge(Li)#1.

Calculated at 295, 352, 609, and 1764 keV
Weighted average = 0.17 ± .07 pCi/g
Density = 2.4 g/cm^3 (~ .7 x background) (4% system uncertainty included)

cc: R. Allen
S. Baker
J. Baldwin

Fermilab

Nuclear Counting Laboratory
Analysis Report

Work Req# 840717-63	Job# 13	Date: 7/19/84
Submitted by: Sam Baker	Wkbk Location: #19 page 139	

Rock from Galena-Plattville Rock Formation. Analyzed for Ra 226. 21.9117 g in petri dish counted at 1 cm from Ge(Li)#1 for 65535 seconds.

Ra 226 = .30 ± .11 pCi/g (background x 1.81 → 81% above background)

Density = 2.71 g/cm^3

cc: R. Allen (WU=7)
S. Baker
J. Baldwin

FIGURE 1.

MODEL FOR A CLOSED TUNNEL WITH AN EQUILIBRIUM CONCENTRATION OF RADON AND NO ACCUMULATED DAUGHTER PRODUCTS INITIALLY

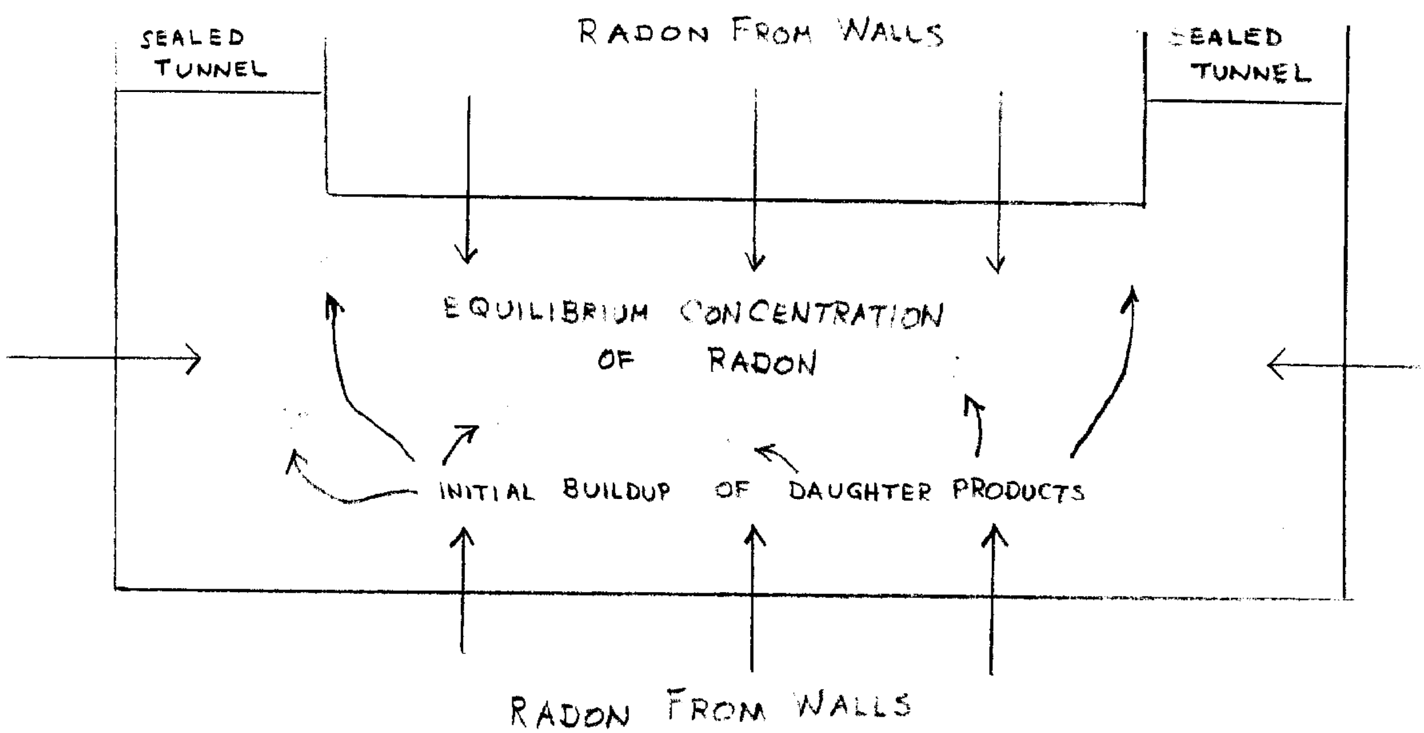
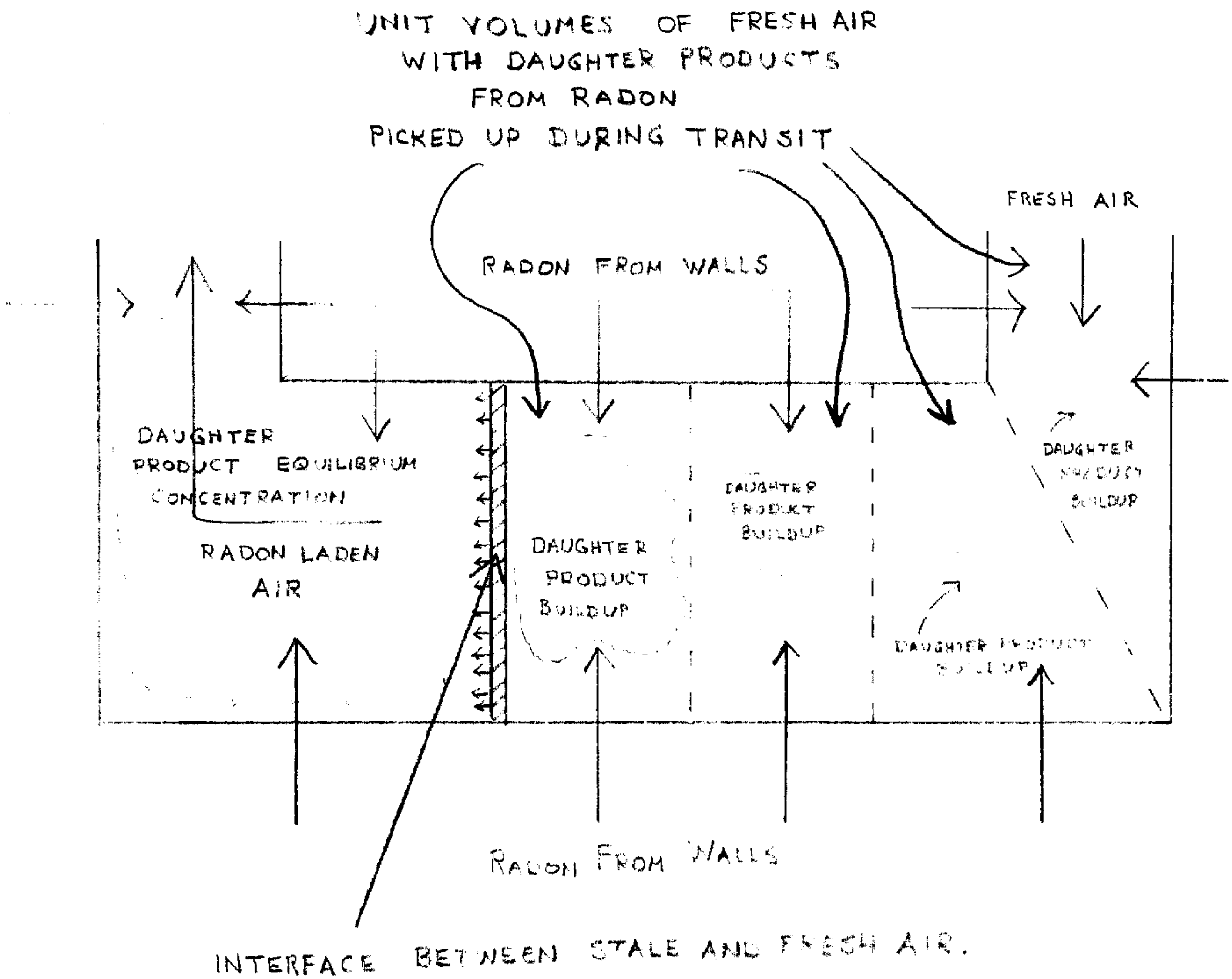


FIGURE 2.

MODEL FOR VENTILATION WITH NO MIXING



MODEL FOR VENTILATION WITH MIXING